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Review

Drying of biomass for second generation synfuel production

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ABSTRACT

Drying is a major and challenging step in the pre-treatment of biomass for production of second generation synfuels for transport. The biomass feedstocks are mostly wet and need to be dried from 30 to 60 wt% moisture content to about 10–15 wt%. The present survey aims to define and evaluate a few of the most promising optimised concepts for biomass pre-treatment scheme in the production of second generation synfuels for transport. The most promising commercially available drying processes were reviewed, focusing on the applications, operational factors and emissions of dryers. The most common dryers applied now for biomass in bio-energy plants are direct rotary dryers, but the use of steam drying techniques is increasing. Steam drying systems enable the integration of the dryer to existing energy sources. In addition to integration, emissions and fire or explosion risks have to be considered when selecting a dryer for the plant. In steam drying there will be no gaseous emissions, but the aqueous effluents need often treatment. Concepts for biomass pre-treatment were defined for two different cases including a large-scale wood-based gasification synfuel production and a small-scale pyrolysis process based on wood chips and miscanthus bundles. For the first case a pneumatic conveying steam dryer was suggested. In the second case the flue gas will be used as drying medium in a direct or indirect rotary dryer.

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1. Introduction

In the planning of biorefineries and production of liquid biofuels for transport via synthesis gas route, several biomass materials, such as wood, forest residues, bark, straw, energy crops, peat, and agricultural residues, are used. In addition to conversion, the pre-treatment of feedstocks is important including transfer, storage, chipping, crushing and drying. For this chain there are many different techniques with variable cost structures. The pre-treatment depends on the feedstock and the concept. In all cases drying will probably be the most challenging step.

Important issues in drying are energy efficiency, emissions, heat integration and dryer performance. In synthesis gas production the feedstocks must be dried to below the 30 wt% moisture content, preferably to about 15 wt%, and in pyrolysis to below 10 wt%. Drying to low moisture contents is problematic and has not been optimised for biomass conversion processes. At this stage for the upcoming demonstration plants it is of utmost importance to survey

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the current drying options and develop effective, preferably low-cost concepts.

Many types of dryer or drying process are encountered in industry. The dryers applied for biofuels have been presented e.g. in references [1–4]. The reader is referred to the literature covering drying theory and practice, e.g. [5]. There are different direct or indirect drying techniques utilising air, flue gas, or steam as drying medium. Forced evaporative drying requires large amounts of energy as well as the provision of often expensive equipment. The impact of drying operation on overall plant efficiency can however be reduced by integration, making use of surplus energy streams within the process.

The present survey aims to define and evaluate the most promising 2–3 optimised concepts for biomass pre-treatment/upgrading scheme in the production of second generation synfuels for transport. The concepts will be defined for two different cases including 1) large-scale wood-based gasification synfuel production, and 2) small-scale pyrolysis process based on wood chips and miscanthus bundles. The most promising commercially available drying processes will be reviewed considering the technologies where water is removed by evaporation. Emphasis will be put on the applications, operational factors and emissions of dryers. The biomass considered is derived either from forestry or agricultural residues, or from dedicated plantations of short rotation coppice (SRC) or herbaceous crops, usually comminuted to the required size.

2. The drying process

2.1. *Material physical characteristics*

The biomass material in question will usually have moisture content on delivery to the plant in the range 30–60 wt%, depending on type, location, time of harvest and period of storage after harvest. Particle size requirements are dictated largely by the bio-energy process, but the biomass at the point of delivery to the drying process is likely to be in large particulate form – e.g. chips or chunks with a largest dimension in the range 10–80 mm. Rotary dryers may accept large and variable particle size fuels, but flash and belt dryers usually require crushing of the fuel to a particle size below 10 mm. The material will have a bulk density in the range 50–400 kgm^{-3}, depending on type and moisture content. Usually the bulk material will have only moderate flow properties, but will readily permit through-circulation of the drying medium.

2.2. *Sources of heat for drying*

Evaporative drying processes require heat exchange, by convection or conduction. Possible sources of heat for drying within a bio-energy plant are 1) hot furnace, engine or gas turbine exhaust gases; 2) high-pressure steam from a steam or combined cycle plant; 3) warm air from an air-cooled condenser in a steam or combined cycle plant; and 4) steam from dedicated combustion of surplus biomass, or diverted product gas, char or bio-oil. The dryer can be a stand-alone process or integrated with, for example, district heating network, pulp mill, saw mill or combined heat and power (CHP) plant.

2.3. *Emissions of drying*

In drying biomass materials organic compounds are released as a result of volatilization, steam distillation and thermal destruction, and cause emissions into the air or wastewaters. Studies on the emissions have been reported, for example, in references [6–15].

The organic emissions can be categorised into volatile organic compounds (VOCs) and condensable compounds. In addition, there are particulate emissions. At low drying temperatures (under 100 °C) the compounds emitted consist mainly of monoterpenes and sesqviterpenes. The VOCs are of environmental concern since they are known to form ground level ozone in the presence of nitrogen oxides [14]. Photo-oxidants are also harmful to humans, as they cause irritation in the respiratory tract and in sensitive parts of the lungs. The condensable organic compounds, such as fatty acids, resin acids and higher terpenes, emitted at over 100 °C, might condense on equipment surfaces and thus cause technical problems. They can also form "blue haze", a discoloration of the exhaust plume, as the flue gases are cooled down after the chimney. The "blue haze" can represent an odour and visual nuisance as well as a potential safety hazard. The thermal destruction of wood materials starts at about 150 °C with the destruction of hemicelluloses, when alcohols, acids and aldehydes are released. In the beginning of drying, thermal decomposition is slight, but the rate of loss accelerates rapidly as temperature is increased further. Such degradation represents an energy loss to the overall process.

In the directly heated atmospheric flue gas dryers, which are the most common dryers for biofuel today, the drying temperature is relatively high and the organic compounds released are diluted in the flue gas and emitted through the chimney, if flue gas condensation after the dryer is not utilised. Clean-up equipment for the exhaust gas stream depends on applicable emissions criteria and regulation, which vary greatly with location. Solid particulates may usually be dealt with cyclones or bag filters. Blue haze is composed largely of sub-micron aerosols, and these are notoriously difficult to remove with conventional gas cleaning techniques.

As a general rule low material temperatures (<100 °C) should be maintained when possible. It would be possible to carry out the drying of wood fuels to about the 10 wt% moisture content without emitting a harmful amount of organic compounds [15]. Prerequisites are e.g. that drying occurs in a bed, the inlet drying gas temperature is not higher than 180 °C and the steam formed is not condensed. The steam released prevents over-drying as long as a part of the material in the bed is still moist. The amount of organics released in the study concerned [15] was below 1 wt% of dry feed material. In newer dryers, such as bed and belt dryers, low drying temperatures are, however, already in use.

Steam dryers are often used in integrated processes where heat recovery through condensing the waste steam from the dryers is utilised. The organic compounds released can be found in the condenser as inert gases, dissolved in the condensed water and as tar, floating on the condensed water.

The majority of the emissions will appear in the steam condensate [16]. The condensate can cause problems for the de-nitrification process of sewage plants. To avoid this, the condensate can be treated by precipitation and biological oxidation before being led to a recipient [14,17]. The small stream of non-condensables can be combusted in an existing boiler.

2.4. *Fire or explosion risk*

A dryer fire or explosion can arise from ignition of a dust cloud if substantial amounts of fines are present, or from ignition of combustible gases released from the drying material. Both causes of ignition require the presence of sufficient oxygen and either a sufficiently high temperature or some other source of ignition. Under conditions found in most dryers, the risk of fire or explosion becomes significant if the drying medium has an oxygen concentration over ~10% (vol.). High explosion pressures of 0.6–0.8 MPa have been measured for different kinds of biomass dust in closed vessels [18]. Under these circumstances high drying medium inlet temperatures should be avoided. High temperatures enhance the risk of explosions by decreasing the required ignition energy to trigger an explosion.

If a low-oxygen environment can be guaranteed, much higher inlet temperatures may be used provided material temperatures do not become excessive, however; prevention of accidental air in-leakage can be difficult and expensive. The most important measure of precaution is to maintain a sufficiently inert atmosphere in the dryer during operation and especially during start-up and shut-down. A high drying temperature creates a risk of spark development and carbon monoxide release through slow pyrolysis and smouldering. Evolution of combustible gases induces a risk of a gas explosion, which may trigger a chain of dust explosions. This is a hazard especially in unintended process stops. Proper ventilation and inertising is required before restart. Carbon monoxide together with dust creates a risk of hybrid explosion, which is very violent. With carbon monoxide present in the atmosphere the safe oxygen level is decreased substantially. The oxygen level has to be kept below 8% (10% − 2% safety margin), with an alarm at 8% and possible interlocking to extinguishing water at 10–11%. During start-up and shutdown of drying processes temporary high oxygen content has to be considered as a risk factor. In superheated steam drying the guaranteed absence of air and oxygen eliminates fire and explosion risks [16].

Biological activity may cause slow self heating in stock piles of wet biomass. Smouldering lumps of biomass constitute a significant ignition source to a violent dust explosion. Spontaneous ignition is another risk factor when handling or storing thermally dried fuels. Proper cooling of the biomass after drying is important to avoid self-ignition problems in intermediate storage bins [18].

3. Dryer types for biomass feedstocks

The dryers for biofuels can be classified, for example, according to the drying medium (e.g. flue gas dryers and superheated steam dryers), or to the heat exchange used (conductive/convective or indirect/direct dryers, respectively). The most common types of flue gas dryers are rotary and flash dryers. The commercial scale steam dryer types are tubular dryer, fluidized bed dryers and pneumatic conveying dryers.

3.1. *Perforated floor dryer*

The perforated floor dryer (Fig. 1) is essentially a batch through-circulation dryer, although it may be configured to operate in continuous mode. Batch methods can sometimes be attractive because of their low capital cost. The dryer would be suited to small plants of perhaps 3 MW_{th} or less.

The basic system comprises a bin with a perforated floor through which hot air is made to flow [5]. Drying performance is strongly influenced by drying medium humidity at inlet, and exhaust gases are normally too humid to be used directly. The wet material forms a fixed bed above the perforated floor. A relatively shallow bed depth of 40–60 cm has been recommended [19]. The batch time is typically a few hours. It is possible to automate the material loading and unloading to varying degrees. The floor may be slowly moving to provide continuous operation. Low velocities and temperatures usually make clean-up of the gaseous exhaust unnecessary.

A drawback with fixed bed through-circulation methods is that they invariably produce a large vertical gradient in moisture content of the dried bed. The dried material therefore needs to be thoroughly mixed before use, and possibly allowed to equilibrate for a period in a buffer store. A low temperature bed dryer, the Renergi LTT dryer [20], developed by Svensk Rökgasenergi AB, allows for utilisation of very low grade heat sources. The temperature of the drying air is about 70 °C. The dryer is based on the counter-flow principle. There are several options for using the bed dryer. It can be used for pre-drying of the feedstock before a conventional drying step or in parallel to the main dryer. The energy-rich gas from the main dryer is fed to a condenser, and the heat reclaimed will be used in the pre-dryer as a drying air.

3.2. *Band conveyor dryer*

Continuous through-circulation dryers have a number of features that make them attractive for biomass feedstocks. The most widely used for biomass is the atmospheric band conveyor dryer (belt dryer), in which the drying medium is blown through a thin static layer of material on a horizontally

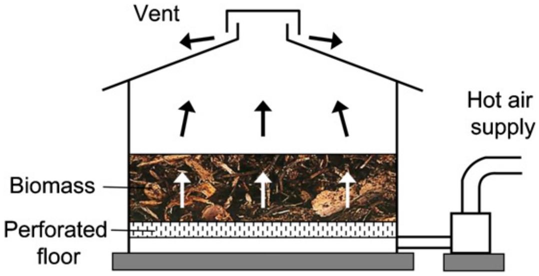

Fig. 1 – Example of a perforated floor dryer.

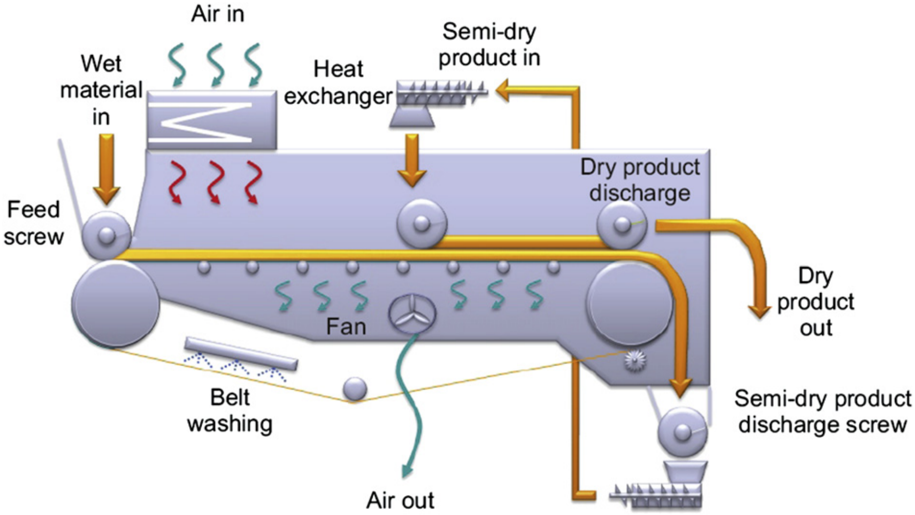

Fig. 2 – Function of a band conveyor dryer [21].

moving permeable band. The band dryer is used for sawdust in pellet production. Band dryers for biomass have been developed by Swiss Combi (Fig. 2), Stela Trocknungstechnik (Laxhuber GmbH) and Andritz AG.

Gas flow may be upward or downward. In the single-stage single-pass design (shown in Fig. 2), a continuous band runs the whole length of the dryer. In multi-stage single-pass designs, a number of bands are arranged in series horizontally, and in multi-pass designs a number of bands are installed one above the other, each discharging onto the band below. The drying medium is usually either air or combustion products, and is forced through the dryer by fans. The dryer is usually divided up into zones through which the drying medium progressively passes. Hot water or low pressure steam is usually used to heat the drying air.

Band dryers can be controlled very easily, in terms of residence time, and moisture content and maximum temperature of the product. Because of the relatively shallow depth of material on the band (usually in the range 2–15 cm) the uniformity of drying is very good. Compared with other dryer types band dryers are voluminous and spacious constructions, especially those with long tunnels. The particle size of the drying material is very important for apparatus size and cost. Drying sawdust (up to 6 mm) needs

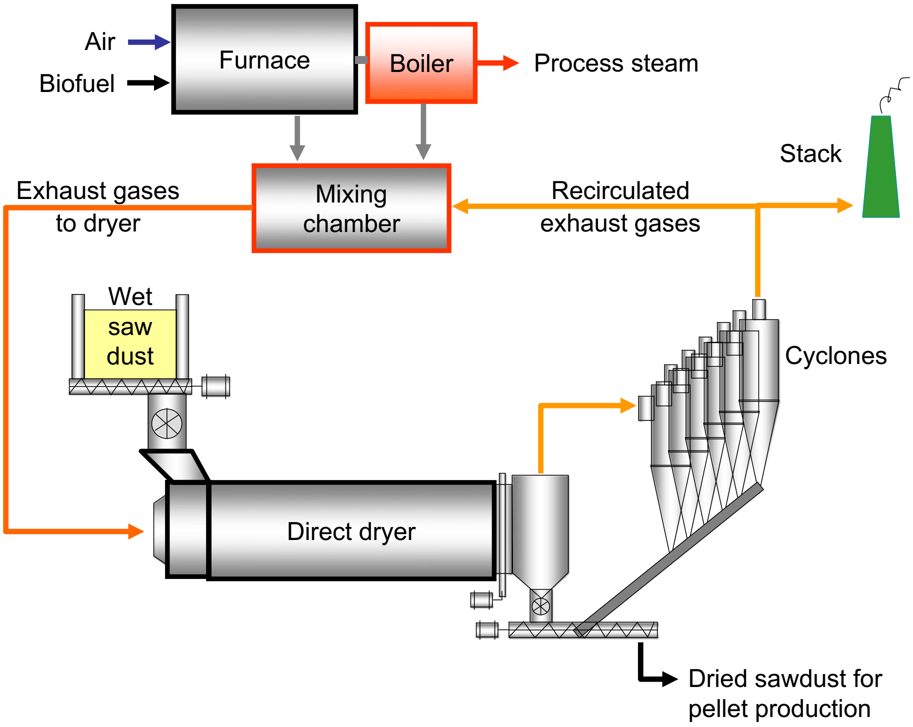

Fig. 3 – Direct rotary dryer for drying of sawdust with flue gases at a pellet plant [22].

smaller band dryers than drying coarse wood chips from sawmills (ca 60–100 mm). Maximum drying air temperature typically is 90–120 °C depending on the end product quality to be achieved. Entrainment of fines with this type of dryer should be low due to low velocities and static material bed. A bag filter, however, may be needed depending on local regulations. On the other hand, large dryer constructions can limit the use of bag filters, and instead water scrubbers may be needed.

3.3. *Rotary cascade dryer*

The direct rotary dryer is by far the most common dryer type found in the existing large-scale bio-energy plants. The dryer consists of a large, inclined rotating cylindrical shell (drum), through which the biomass moves. The shell diameter can range from <1 m to >6 m depending on throughput. Material is loaded into the shell at the upper end, passes along the shell and exits at the lower end. The drying medium, either heated air or combustion products, may flow either way, although parallel-flow is usually necessary for heat-sensitive materials including biomass. On the inside of the shell are a number of longitudinal flights which lift the material and cascade it in a uniform curtain through the passing gases.

Overall heat transfer is less effective than for through-circulation systems, and significantly larger volumes of gas are required. When drying wood chips using exhaust gas, inlet temperatures are normally between 250 and 400 °C. Many systems are offered with heating equipment at inlet, often in the form of a gas burner. Fines separated in the exhaust cyclone can be used to fire a small combustor to provide additional hot gases for the dryer. In addition, hot flue gases from a heating plant or a CHP plant can be used (Fig. 3). The unavoidable carry-over of entrained material and the relatively large gas volume flow rates make sizeable cyclones and bag filters usually essential. Sealing problems leading to air in-leakage have been a weakness in many installations trying to maintain a low-oxygen environment.

3.4. *Indirect tubular steam dryer*

Indirect heating can also be employed in rotary dryers, when a suitable source of steam is available. The most usual form of such a dryer is known as a steam-tube dryer. Steam tubes running the full length of the dryer are arranged in a number of concentric rows moving inwards from the dryer shell. The number of rows will depend on the nature of the feed. The tubes are fixed to the dryer end plates and rotate with it. Heat transfer is by conduction from surfaces at or close to the steam temperature. Saturated steam is normally used, typically at 0.6–1 MPa, and the steam passages will be designed to be fully condensing. Capital costs can, however, be high, due, for instance, to the tubing requirements and rotating seals.

Haarslev Industries Rotadisc dryer [23] presented in Fig. 4 is applied for sawdust at three pellet plants of Vapo Oy in Finland. The drying system is closed and the exhaust gases are cleaned with a bag filter. Critical factors in design are the drying steam pressure and the particle size of the material. Ponndorf Maschinenfabrik GmbH delivers drum dryers with steam-tube heat exchangers for wood chips drying. Swiss Combi has developed an indirect ecoDryer with a closed-loop vapour system and integrated incineration [24]. The dryer allows a large variation with respect to plant size (evaporation of water 5–40 t h^{-1}) and can be powered by different energy sources, such as natural gas, oil and wood burning. The dryer has low emission values, low energy consumption due to small exhaust volume, and low fire hazard potential due to an inert atmosphere.

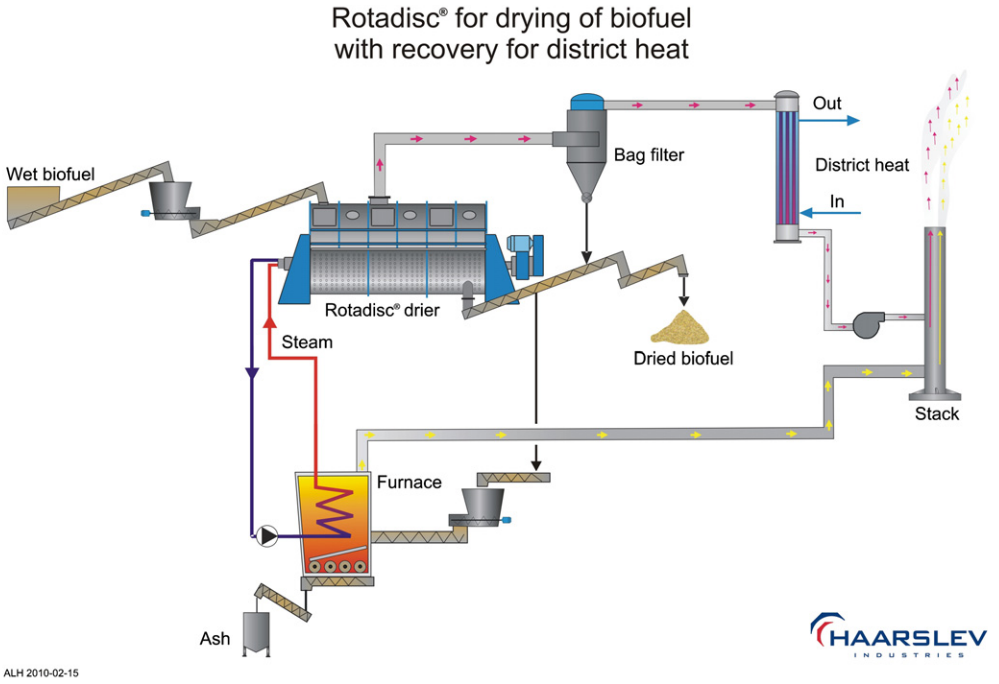

Fig. 4 – Rotadisc® dryer of Haarslev Industries for biofuel [23].

An indirect two-stage tubular drying technology was selected for drying of sawdust and wood materials in a new bio-energy combine of Västerdala Bioenergi AB in Vansbro, Sweden, in 2006 [22,25]. Pellet production was combined with local district heating production. The aim was to minimize the net heat energy required for the drying by using pre-drying and recovering all waste heat. The dryer was delivered by AB Torkapparater, and the condensers by Svensk Rökgasenergi AB. The final drying is carried out in a high temperature (HT) dryer, heated with 1.6 MPa steam from the biofuel boiler (Fig. 5). The hot condensate is used as drying energy in the low-temperature (LT) pre-dryer. Flue gases from the boiler at about 300 °C are used for ventilation in the dryers. The flue gas outlet temperature in the pre-dryer is about 105 °C and in the HT dryer about 200 °C. Evaporation capacity is approximately 6–7 t h^{-1}. Flue gas from the boiler is used for conveying the sawdust through the dryers. About 85% of the heat used for drying has been recovered.

The indirect tubular dryers (Fig. 5) provide a closed system and inert atmosphere in the dryers. The fines in flue gases from both the dryers are separated in cyclones. The flue gases are condensed and lead through a wet electrostatic precipitator into the stack. The wastewaters are treated in three consecutive sand beds and the pH is adjusted by lime before the water is let to the sewer. The tars formed can principally be burnt in the grate furnace; extracting the tar from the surface of the condensate can, however, be difficult.

3.5. *Fluid bed dryer*

Conventional fluid bed dryers using hot air or exhaust gases could be suitable for biomass feedstocks, although as yet there are very few installations. Such processes are generally fast and efficient, and equipment size is relatively small compared with other techniques. In fluidized bed drying the gas velocity blown upward through a layer of particles is such that all the particles are suspended in the upward flowing gas. Steam fluidized bed drying tends to combine the advantages of superheated steam drying and the excellent heat and mass transfer characteristics of a fluidized bed.

A pressurised steam fluid bed dryer developed by Niro Inc. (now GEA Process Engineering Inc.) primarily for brewing, food and sugar processing industries, has been installed to biofuel plants in Sweden, for drying wood chips at Borås Energi and bark at Södra Cell Mönsterås [26]. The dryer was installed and integrated in the process of the Borås Energi AB plant in 1994, to increase the efficiency of the power plant. In addition, the dry wood displaced coal in the fuel mix [27].

Recycled moisture evaporated from the feed forms the low pressure steam drying and fluidising medium for the Niro dryer. The low pressure steam passes through an internal heat exchanger to be heated indirectly to about 200 °C by high-pressure steam (max. 2.5 MPa (g), 250 °C), before returning to the bed distributor plates. The continuously discharged flow of excess evaporated steam is at about 0.28 MPa (g) and 150 °C, and may therefore be used as process steam elsewhere. The dryer is suitable for products with a particle size from 0.5 mm to 50 mm. The Niro dryer is considered very efficient because of the utilisation of the recovered steam, although a suitable external use must exist. In a bio-energy plant this would only be the case with cogeneration applications. In addition, it has excellent environmental performance as a result of the system being fully closed with no gaseous emissions to atmosphere. Capital cost of the Niro dryer is high, and the dryer is likely only suited to relatively large-scale plant.

A recently developed method designed by the company Ventilex B.V. [28] for biomass drying is sub-fluid bed drying (Fig. 6.). In the dryer, solid particles are brought in a fluid state by an upward-moving flow of gas in combination with vertical mechanical shaking of the fluid bed distributor plate. Thus the gas and product are intensively mixed, resulting in high heat transfer rates and proper drying conditions. Residence times

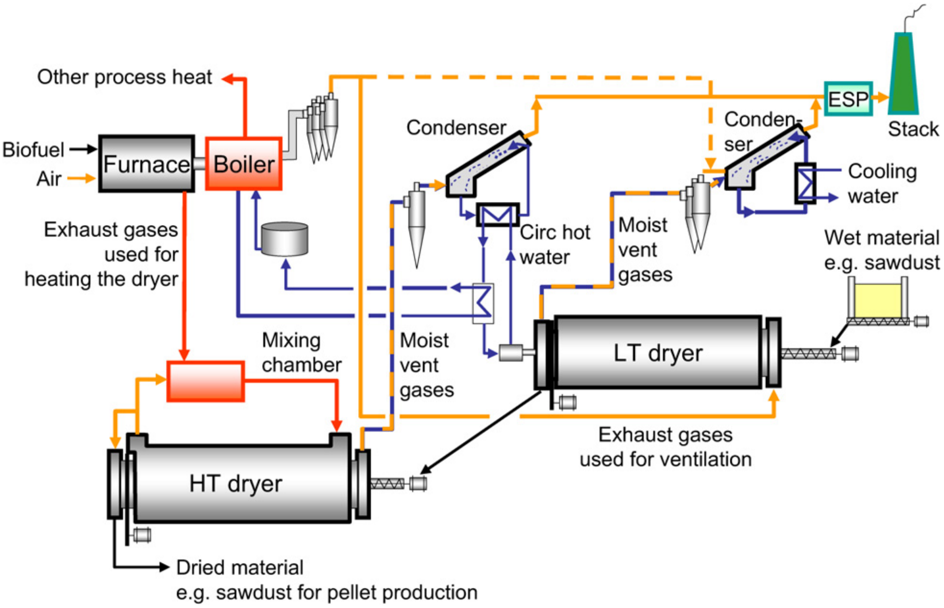

Fig. 5 – The scheme of the two-stage indirect drying process at Vansbro pellet plant in Sweden [22].

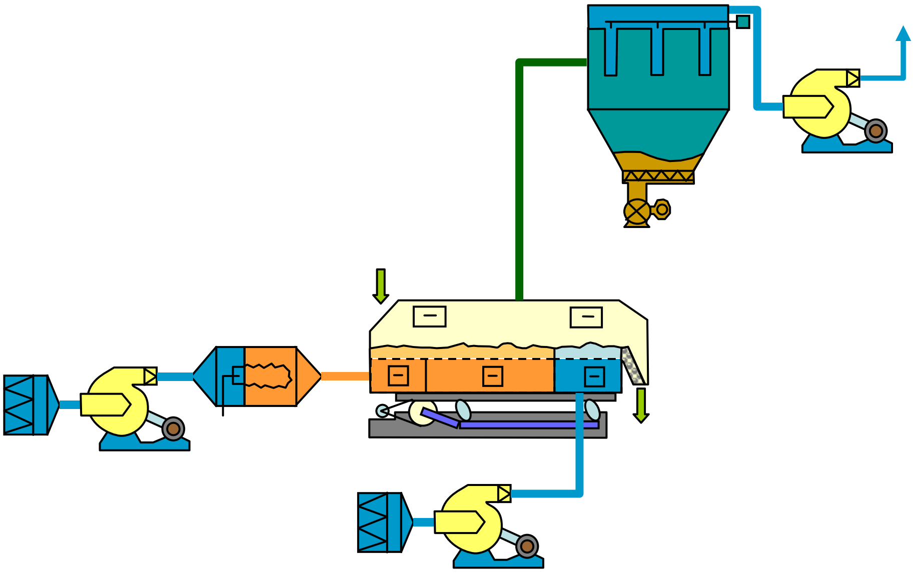

Fig. 6 – Flow scheme of a sub-fluidized bed dryer with cooling [28].

up to 2 h and drying temperatures up to 600 °C are possible. The layer thickness of the product can vary from 5 to 60 cm with this process method. Dust is removed from the gas stream via cyclones and a bag filter.

A two-stage sub-fluid bed dryer system with energy recovery has been designed to dry wood chips to 15 wt% moisture for the torrefaction system of Energy Research Centre of the Netherlands. The maximum linear dimension of the wood chips is in the range 15–40 mm. Due to the recovery of heat via the condenser, the total net energy demand is low, approximately 2.2 MJ kg^{-1} of water evaporation. Heat recovery thus compensates for most of the heat losses in the drying process. Especially in combination with a torrefaction plant, the sub-fluid bed drying system is very well suited for further heat recovery.

3.6. *Pneumatic conveying steam dryer*

Pneumatic conveying dryers achieve rapid drying with short residence times by fully entraining the material in a high velocity gas flow, usually air. They are normally used for drying very small particles. However, a closed-loop pneumatic conveying dryer has been developed in Sweden for drying biomass at sizes of up to 50 mm, using only indirectly heated steam from the liberated moisture as the conveying and drying medium [29]. The dryer developed in the early 70’s by Chalmers University of Technology, Gothenburg, and MoDo-Chemetics AB, is now marketed as the Exergy steam dryer by Swedish Exergy AB. The dryer includes a high degree of energy recovery and zero gaseous emissions [30].

The superheated steam circulates in the dryer at a pressure of 0.2–0.6 MPa and pneumatically transports the particles through the tube side of a series of tubular heat exchangers. The heat for drying is supplied by heating steam which is condensed on the shell side of the heat exchangers, usually at a pressure of 0.8–2.5 MPa. The dried material is separated from the steam in a cyclone, and the steam is recirculated by the fan. The excess steam evaporated in the dryer is continuously bled off from the system and is available at a pressure of 0.2–0.6 MPa as process steam. Alternatively, the vapour can be recompressed for internal use, as is done for instance in a peat briquetting factory. The residence time of material in the dryer is 10–30 s, and good uniformity in final moisture content is achieved.

Installations are typically large, in excess of 10 t h^{-1} evaporation. The Exergy steam dryer was first taken into commercial use at Rockhammar mill in Sweden for drying of pulp. The first commercial drying unit operating on hog fuel was installed in Husum pulp mill in the 1980s. A complete Exergy steam drying system was supplied to the Danish Energi E2 A/S for a wood pellet mill in Koege, Denmark, in 2003. Skellefteå Kraft AB commissioned a new dryer in Storuman pellet plant in 2008. Previously, a similar system was supplied to the pellet plant of Skellefteå Kraft in Hedensby, Sweden, in 1998. Both pellet plants are integrated to biomass fired CHP plants.

In the Skellefteå Kraft plant, the incoming sawdust is sieved before it is fed into the dryer, operated with the steam (0.7–2.6 MPa) condensing outside the tubes. Circulating superheated steam (0.4 MPa) carries the drying material inside the tubes. The dryer consists of two 30 m high vertical condensers, with 121 tubes, each diameter is 110 mm. The fuel is transported through the tubes by a large fan and stays in the drying zone for about 30 s to reduce the moisture content to 9 wt%, before the pellet mills. The drying steam from the CHP plant condenses outside the tubes and therefore does not mix with the steam, which is produced from the wet fuel. The pure condensate from the dryer can be used again. The pressurised steam dryer enables energy recovery at high temperature levels. When planning the combined pellet and CHP plant great emphasis was placed on the efficient use of energy and the possibility to use this energy to produce more electricity. The maximum output of the plant is 4.9 MW_{el}.

3.7. A summary of dryers applied for biomass

Typical operational data of the main dryers applied for biomass and presented above have been summarized in Table 1.

Table 1 – Performance data for dryers applied for biomass.

Dryer	Band dryer	Rotary dryer	Steam rotary dryer	Pressurised fluid-bed dryer	Pneumatic steam dryer
Feed	Sawdust, wood shavings, wood chips	Sawdust, wood chips, bark	Sawdust, wood processing	Wood chips	Sawdust, bark, forest residues
Feed flow, t h^{-1} (dry)	8–9	6–7	5–6	9	25
Moisture inlet, wt%	50–60	50–60	50–60	50–60	50–60
Moisture outlet, wt%	10–15	10–15	10–15	10–15	10–15
Drying medium	Air, flue gas (90–120 °C)	Air, flue gas (250–400 °C)	Steam (ambient pressure)	Recycled LP[a] steam (0.3–0.4 MPa)	Recycled LP[a] steam (0.3–0.4 MPa)
Heating medium	Hot air	Flue gas	HP[b] steam (0.6–1 MPa)	HP[b] steam (2.6 MPa)	HP[b] steam (0.7–2.6 MPa)
Evaporation capacity, t h^{-1} H_2O	10	7–8	6–7	5–40	25
Evaporation energy demand, MJ kg^{-1} H_2O	4–5	4–5	3–4 0.8–1 (energy recovery)		2–3 0.5–0.7 (energy recovery)

a Low pressure.
b High-pressure.

4. Case definition and drying concepts

4.1. Dryer integration

It is usually foreseen that production of synfuels will be integrated to existing pulp and paper mills or to biomass power and CHP plants. The key issue when selecting the drying process to a gasification or pyrolysis plant is the integration of the drying process with the energy infrastructure of the main process. This enables the utilisation of available steam supply or low value surplus energy streams like low pressure steam and hot water. Also, depending on the drying process, residual energy streams from the dryer can be utilised to produce low pressure steam or district heating. A common requirement is also that no emissions to the air are allowed from the drying process.

The steam dryer makes it possible to recover 80–90% of the drying energy as low pressure steam or district heating. Pressurised dryers are more complex, especially with regard to feeding of the biomass into the dryer at 0.3–0.4 MPa, but condensing the evaporated steam and producing low pressure steam may be more favourable than only producing hot water. The pressurised dryers need medium or high-pressure steam for drying energy. Ambient pressure steam dryer is usually integrated to a medium pressure steam net and the condensate is used for district heating purposes.

If an excess of low value steam or hot water is available at the plant, the band dryer is a possible option. Technically the band dryer is of a fairly simple construction but requires much space. Energy from the drying air is not usually recovered but the humid air stream may need to be clean from dust particles. If plenty of space and low value energy sources are available at the plant site, pre-drying in stock piles or perforated floor-type intermediate storage dryers may be feasible.

4.2. Case 1: large-scale wood-based gasification synfuel production

The large-scale synfuel production case defined was based on the gasification process. The size of the plant was selected to be 250 MW. The feed of the dryer will be 100 t h^{-1} at a moisture content of 50 wt%. The scale of the size reported to suit Finnish conditions is 200–400 MW feed due to procurement of the feedstock (biomass residues) at a competitive price, feasible integration of the syngas process with pulp and paper mills, and realisation of fluidized-bed gasification as one or two trains, only [31,32]. The biomass will be dried to the moisture content of 15 wt%. The particle size will range from 10 to 50 mm. The feedstock will be woody biomass: bark, sawdust and forest residues. A general layout of a process for producing biomass-derived synthesis gas and integration of a Fischer–Tropsch plant to a pulp and paper mill is schematically presented in Fig. 7.

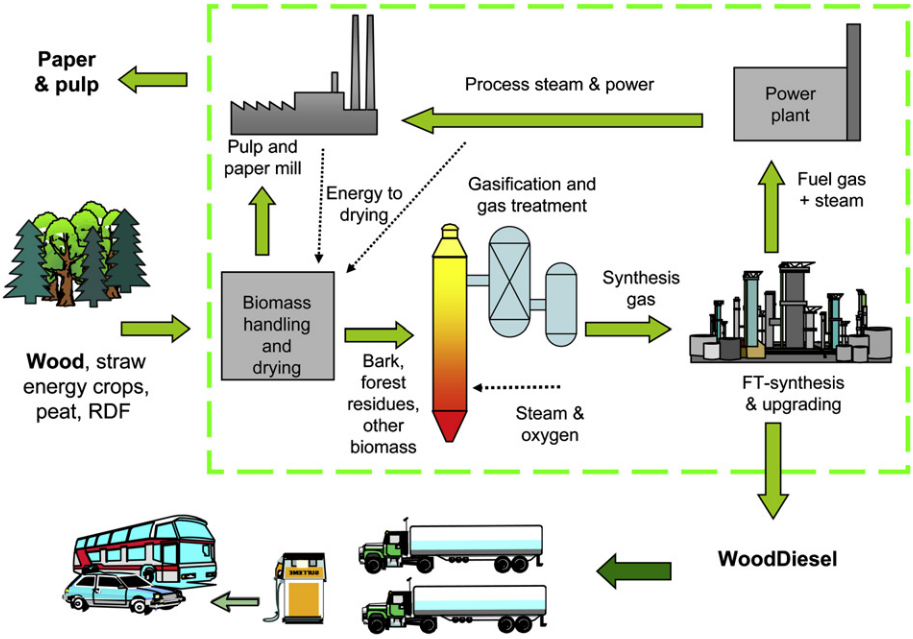

Fig. 7 – **General layout of a process for producing biomass-derived synthesis gas and integration of a Fischer-Tropsch synthesis plant to a pulp and paper mill.**

A dryer applied for large-scale drying installations should be selected for the purpose. A pneumatic conveying steam dryer will be potential. It allows the recovery of low pressure steam and zero gaseous emissions. The condensate can be treated separately. The dryer can be integrated to the existing heat or energy sources of the process. The indirect steam drying technique seems to be the most attractive and suitable enabling the recovery of latent or waste heat, one example is presented in Fig. 8. If low-temperature steam will be available, it might be reasonable to pre-dry the biomass first, for example, in a low-temperature bed dryer or belt dryer, prior to the main dryer.

4.3. *Case 2: small-case pyrolysis plant based on wood chips and miscanthus bundles*

A pyrolysis plant using wood chips and miscanthus bundles was defined for a small-scale stand-alone synfuel production case.

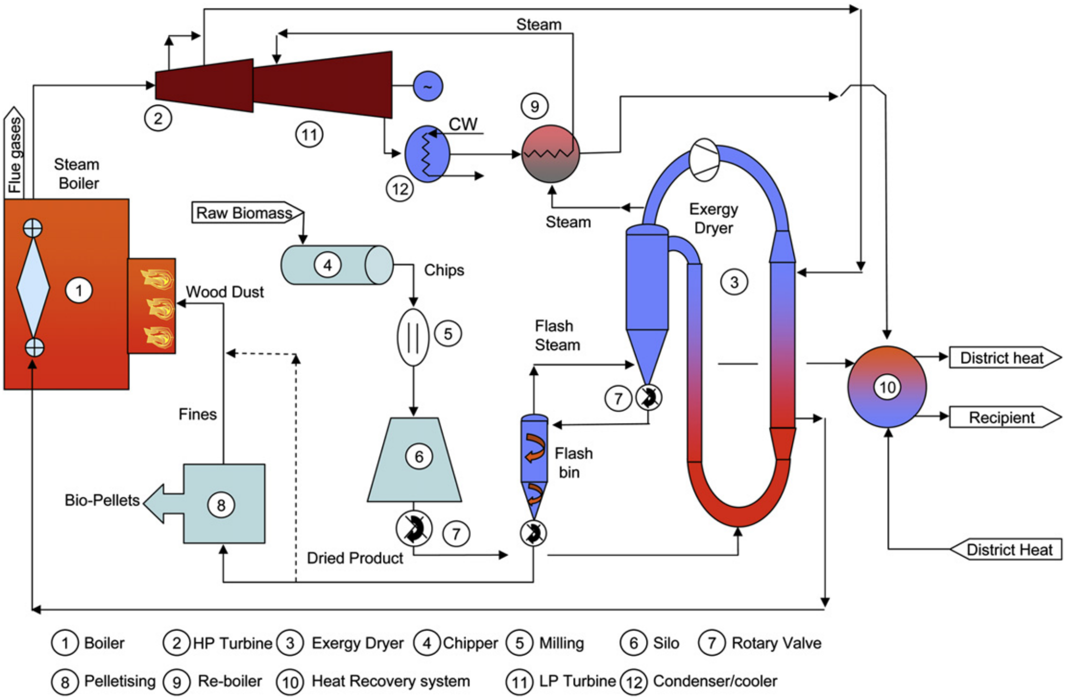

Fig. 8 – **Example of energy integration of Exergy dryer at a pellet production facility [33].**

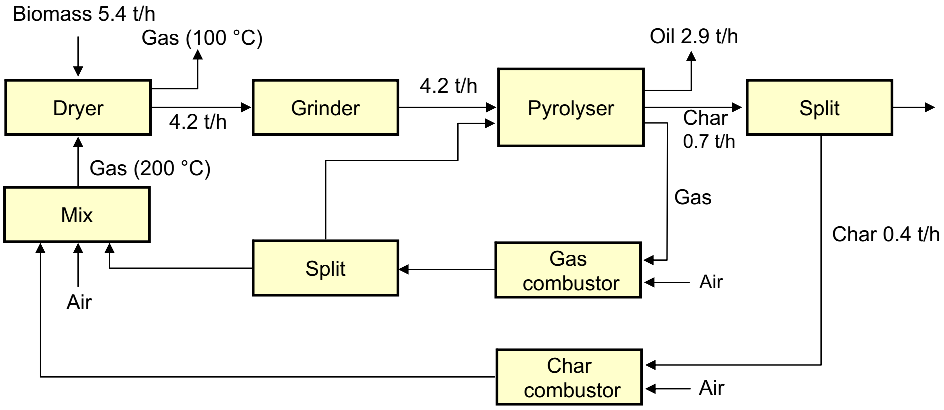

Fig. 9 – **Pyrolysis plant simplified flow sheet.**

In the first concept SRC willow chips will be used as feedstock. The chips (3.8 dry t h^{-1}) with 30 wt% moisture content and maximum linear dimension in range 5–50 mm, are delivered to a single pyrolysis plant by road. The size of the pyrolysis plant is 100 t d^{-1} of biomass (4.2 t h^{-1}) at 10 wt% moisture. Biomass will be stored on site as chips (3 days' operation), dried to 10% moisture and ground to maximum particle size of 2 mm on site prior to feeding to fluidized bed pyrolysis unit. The yield of bio-oil will be 71 wt% of dried feed and the yield of surplus char 11 wt%. Bio-oil is then supplied to local heating or diesel engine CHP schemes by road. The flow sheet and mass balance are given in Fig. 9. For the drying of the wood chips the flue gas at 200 °C will be used as drying medium in a direct or an indirect rotary dryer.

The second concept is based on bundled miscanthus stems. The feedstock (91 dry t d^{-1}) at 25 wt% moisture content is delivered by road to the single pyrolysis plant presented above. Biomass will be stored on site as stems (3 days' operation), chopped and dried to 10 wt% moisture, and ground on site to maximum particle size of 2 mm prior to feeding to the pyrolysis unit. The dryer for the stems was suggested to use existing flue gas at 200 °C as the drying medium and be a direct rotary dryer. A rotary drum dryer is a common choice when drying different kinds of feedstock in a stand-alone plant and utilisation of residual energy streams is not an issue. The investment is usually favourable compared to more efficient and complicated systems.

5. Conclusions

Biomass feedstocks need often to be dried prior to the conversion process, such as pellet production, pyrolysis and synthesis gas production. A number of different dryer types may be suited for the purpose, and the final choice should be made after careful consideration of operational and economic factors specific to the application.

At small scales costs are likely to dictate either a batch perforated-floor technology using heated air, or a simple band conveyor using exhaust gas or heated air. At intermediate scales, the rotary dryer will probably continue to dominate, with band conveyor designs being a possible alternative. At larger scales in steam cogeneration applications, the use of steam dryers may offer efficiency advantages. It makes recovery of low pressure steam or hot water for district heating possible. The closed system assures zero gaseous emissions. In stand-alone applications a low investment is usually emphasised, and correspondingly less energy efficient solutions like flue gas dryers (drum dryers) or band dryers are preferred.

The environmental effects of dryers such as emissions and fire or explosion hazards have to be considered. The gaseous and aqueous emissions should be maintained low. The material temperatures should be low in drying and a sufficiently inert atmosphere in the dryer, especially during start-up and shut-down, is important. In the latest dryer installations the emissions have already been considered. The exhaust gases are cleaned mostly with bag filters and cyclones, and the wastewaters are treated with sand beds and their pH is adjusted prior to being led to the sewer.

In drying applications integration has become increasingly important. In the large-scale wood-based gasification synfuel production case, a pneumatic conveying steam dryer selected for the purpose enables the integration to the existing heat or energy sources of the main process. The condensate from the steam dryer can be treated separately. In the small-scale stand-alone pyrolysis case based on SRC willow chips feedstock, a direct or an indirect rotary dryer using the flue gas at 200 °C as drying medium is reasonable.

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